World Conference on Timber Engineering Oslo 2023

MEASUREMENT OF DIRECTIONAL CHARACTERISTICS OF MOISTURE TRANSPORTATION IN WOOD UNDER HEATING

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ABSTRACT: Time variations in moisture content and temperature inside Japanese Cedar *(Cryptomeria Japonica)* specimens exposed to steady heating from three different directions were measured with small resistive sensors, as developed by Suzuki et al [1]. Radial, tangential, and longitudinal heating at 4.5 kW/m^2 with Cone Calorie Meter were conducted to investigate the anisotropy of water transfer and its effect on the rise in temperature under fire heating; specimens were controlled in air-dry or bone-dry conditions. As a result, longitudinal water transfer was large and observed most frequently in the three heating directions, because of which tracheid worked as a path of transporting vapor away from the heating surface. Moreover, the rise in the temperature of Air-Dried specimens was suppressed compared to that of Bone-Dried specimens, especially in longitudinally heated specimens, and the temperature difference was up to 4.6 times larger than that of radially and tangentially heated specimens. It was because the heating caused by re-condensation was the smallest in longitudinally heated specimens, according to the largest water transfer.

KEY WORDS: Moisture Content, Heat and Water Transfer, Sorption, Anisotropy, Cone Calorie Meter, Japanese Cedar

1 INTRODUCTION

With the increasing number of high-rise wooden buildings, the importance of accurate prediction of the mechanical properties of wooden member has increased. Water content in wooden members is a key factor that affects the decrease in the mechanical property of wooden members under fire. Kaku et al. [2] reported that the moisture content and rising temperature reduced the mechanical properties at high temperature; the Young's modulus of Japanese Cedar specimen at high moisture content near 100 ℃ is was found to be as low as that of the dry specimen at 200 ℃. It was confirmed that the water in the wooden members exposed to fire transferred as vapor from high temperature part to low temperature part for recondensation [1]. Considering the rise in moisture content, the Young's modulus of inner part of wooden fireproof beam after heating for 2 h near 100 ℃ was estimated to decrease as low as that of 230 ℃ in dry wood [3].

As for anisotropy of properties of wood, that of thermal conductivity is discussed by Maku [4] that longitudinal thermal conductivity is approximately 2.5 times larger than that of the radial or tangential ones; Kawabe et al. [5] measured longitudinal permeability and found it to be significantly larger than the transverse ones.

Moreover, structural members are heated three dimensionally under fire heating as shown in Figure 1, and there is temperature incline in longitudinal direction, because the wooden thermal conductivity is significantly small. Therefore, it is assumed that the water transfer has anisotropy as thermal and vapor pressure incline as a driving force of water transfer has anisotropy. Furthermore, it can affect the moisture content distribution in wooden structure members. Although, water transfer in wooden members is measured in previous studies, the anisotropy of wood is not considered. In this study, to measure the time variation of local moisture content caused by anisotropy of wood, three directional steady heating tests were conducted on two conditions of Japanese Cedar (*Cryptomeria Japonica*) specimens.

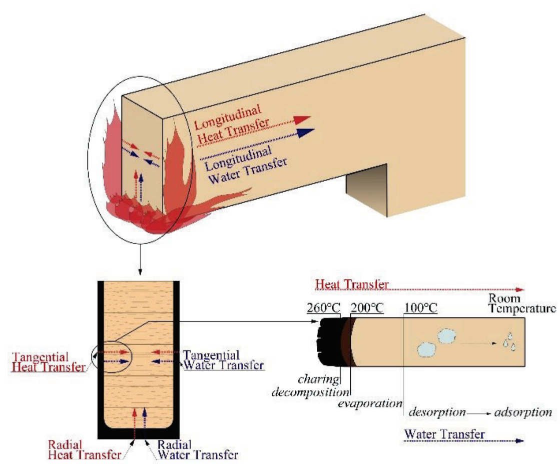

***Figure 1**: Moisture Transfer in a Timber during Fire Heating*

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https://doi.org/10.52202/069179-0222

2 EXPERIMENTAL METHOD

2.1 METHOD

Each Specimen were heated with Cone Calorie Meter, with heat flux of 4.5 kW/m^2 for 60 min. The incidence of heating flux supposes the heating situation of load-bearing part of fireproof timber which temperature lower 180 °C. The temperature and moisture content distribution of four points in specimens were measured. Temperature was measured with thermocouples in each 2 s. Moisture content was measured with resistance moisture meter proposed in previous paper [1]. The resistance between the two electrodes installed in the specimens was measured and converted into moisture content by a reported calibration curve. The two electrodes were lined up parallel to the tangent of growth ring with a 10 mm gap between them. A couple of electrodes separated by 2 V were applied to measure resistance in interval of 16 s, because it takes 4 s to measure the resistance of each point.

2.2 SPECIMENS

Specimens are made of heartwood of Japanese Cedar (*Cryptomeria Japonica*). As shown in Figure 2, size of 100×100×45 mm, and the largest surface were heated. Four sets of thermocouples and moisture sensors were inserted from non-heating surface in each specimen, two sets were placed at 20 mm from heating surface, and other two sets were placed at 30 mm from the heating source. Each measuring point was named as below.

Moisture Content or Temperature – Depth – No.
[MC or T] – [20 or 30] – [a or b]

The side surface of specimens was sealed with aluminum foil tape with an aim to stop the water transformation orthogonal to a heating direction.

2.3 EXPERIMENTAL CONDITIONS

Table 1 shows the specimen list. The heating directions and initial moisture content were the parameters. As shown in Figure 2, the heating directions were radial, tangential, and longitudinal, which are referred to as R, T, L, as shown below.

The initial moisture contents were air-dry and bone-dry. Air-dry specimens were stored in a plastic jar. The relative humidity in the plastic jar was controlled by saturated NaCl solutions until the weight became stable. The average moisture content of the R, T, L specimens are in the range of 12.0–13.6%. The initial moisture content of each specimen was obtained by drying a sample, which was cut from as same wood as each specimen and stored in the same condition as the specimen. First, the bone-dry specimens were dried in the drying furnace at 90 °C until the weight of specimens became stable, after that the specimens were stored in a tightly sealed plastic bag with silica gel desiccant in room temperature. In Bone-dry condition tests, only the thermal couples were inserted to clarify the anisotropy of heat transfer without the effect of water.

***Table 1**: Condition of specimens*

Condition of Moisture Content	Heating Direction	ID		Bone-Dry Density* [g/cm^3]		Width of Annual Rings [mm]		Initial Moisture Content* [%]	
					Average		Average		Average
Air-Dry	Radial	AR	AR-1	0.260	0.257	2.4	3.7	13.6	13.6
			AR-2	0.252		4.4		13.3	
			AR-3	0.260		4.2		13.9	
	Tangential	AT	AT-1	0.287	0.274	4.1	4.2	13.4	13.5
			AT-2	0.287		3.7		13.4	
			AT-3	0.250		4.8		13.8	
	Longitudinal	AL	AL-1	0.251	0.254	4.9	5.2	11.5	12.0
			AL-2	0.256		5.3		12.2	
			AL-3	0.256		5.3		12.2	
Bone-Dry	Radial	DR		0.260		4.8		-	
	Tangential	DT		0.278		4.5		-	
	Longitudinal	DL		0.251		5.4		-	

* Values of thin samples which were cut from specimen

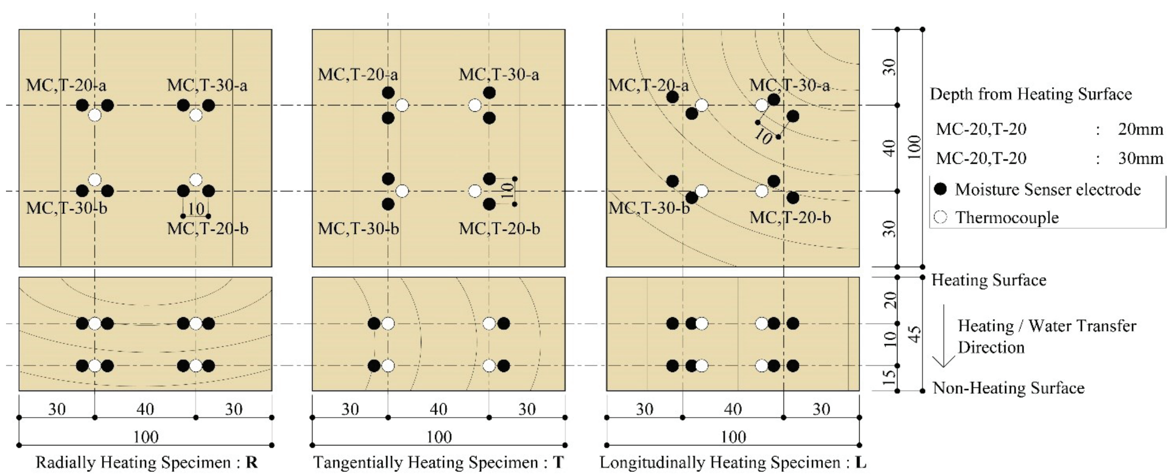


***Figure 2**: Position of Thermocouples and Moisture Sensors*

3 RESULTS

3.1 BONE-DRY SPECIMENS

Figure 3 shows the temperature variation of Bone-Dry specimens in each condition and the difference of the rise in temperature among the longitudinally heated specimens (DR), radially (DR), and tangentially (DT) heated specimens, Figure 4 shows temperature increase rate of Bone-Dry specimens in each condition and the differences as same as those shown in Figure 3. We obtained the rate of temperature rise as a moving average of the two minutes of temperature rise for each specimen and averaging them.

The difference of the rise in temperature of DR and DT were small, that is, 0.2 to 3.6 ℃. The temperature rise of DL was found to be 34.7 ℃ higher than that of DR, and DT after 20 min. The difference was increased 25.5 ℃ on 20 min to 34.7 ℃ on 60 min at 30 mm depth. After 20 min, the difference in the rise in temperature differed in the cases of 20 mm depth 30 mm depth; that is, the temperature rise was 8.4 to 14.7% smaller in the case of 20 mm depth compared to that in the case of 30 mm depth. However, until 20 min, there was a difference between the temperature difference in the case of 20 mm depth and that of 30 mm depth.

Moreover, Figure 4 shows that the rate in temperature increasing of DL was larger and had sharper peak than that of DR and DT. The difference of the rate increased quickly in the maximum rate of 4.0[℃/min] until 8.0min at 20mm depth, and maximum rate of 2.7[℃/min] until 19.8min at 30mm depth, then those differences kept increasing similarly at an average rate of 0.25 [℃/min] for 60 min.

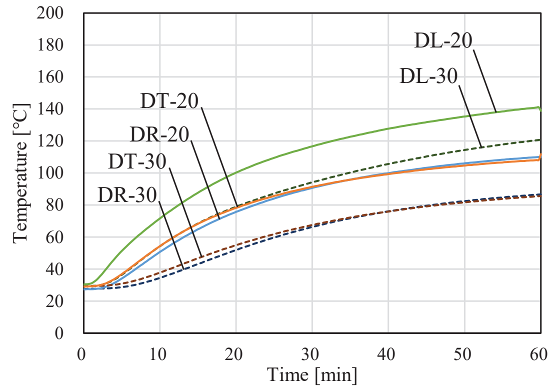
The temperature difference between DL to DR and DT was due to the anisotropy of thermal conductivity; thermal conductivity of longitudinal direction is 1.5 to 2.8 times larger than that of the radial or tangential direction [6]. Moreover, the difference of thermal conductivity caused the difference of temperature increasing rate of 0.25 [℃/min]; therefore, for the cases of 20 mm and 30 mm depths, heating was considered to be steady after 8.0 and 16.8 min, respectively, according to the slope of temperature difference became nearly constant and thermal conductivity is thought to be the critical factor of temperature increasing in materials with equal heat specific heat and density.

3.2 AIR-DRY SPECIMENS

3.2.1 INITIAL MOISTURE CONTENT

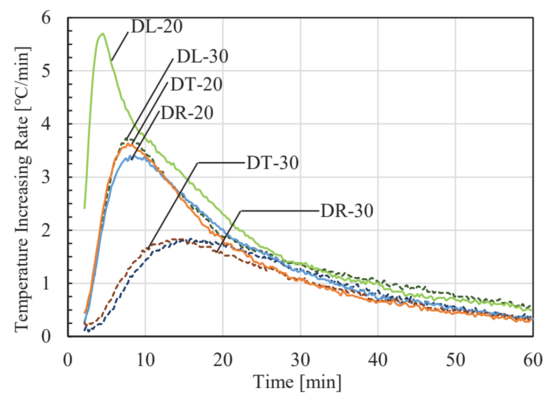
Figure 5 shows the relationships of the initial moisture content obtained by sample drying and initial moisture content obtained by moisture sensor.

Initial moisture content obtained by sample drying was distributed in the range of 11.5–13.9%, while the initial moisture content measured by the moisture sensor was in the range 10.9 – 19.8%. Although several values obtained by moisture sensor were higher than those obtained by sample drying, a few of them were lower. The difference between the values obtained by sample drying and moisture sensor was in the range 2.5–6.5% in all the specimens and average value of the difference was 1.8%. The factors affecting the initial moisture content remains unclear, and these factors can be categorized into two groups: (1) The factors affect the resistance of moisture sensors, and (2) the factors affect the moisture content in



*: Each line shows mean value. “-20”, “-30” indicate values at 20, and 30mm depths, respectably

***Figure 3**: Time Histories of Temperature of Bone-Dry Specimens*



*: Each line shows mean value. “-20”, “-30” indicate values at 20, and 30mm depths, respectably

***Figure 4** Time history of the Rate of Temperature Rise of Bone-Dry Specimens*

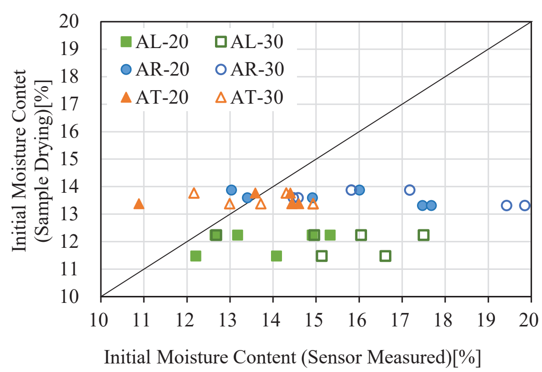


***Figure 5**: Relationships of initial moisture content obtained by sample drying and by moisture sensor*

https://doi.org/10.52202/069179-0222

wood. For instance, the first group includes the amount of adhesive used to fix electrodes in wood and width between the electrodes; lower amount of adhesive or larger width of electrodes causes higher resistance which results in lower moisture content value. The other group includes distribution of moisture content in a wood specimen. In this experiment, we cannot clarify the factors affecting the difference, and identifying the causes is a future issue.

3.2.2 TIME HISTORY OF MOISTURE CONTENT AND TEMPERATURE

Figure 6 shows the time history of temperature and moisture content of typical one specimen of each condition. Figure 7 shows the range of increase of moisture content and range of decrease of moisture content of each condition. We obtained increase and decrease range of moisture content as below Equation (1) and (2). Increase range of moisture content indicates maximum moisture concentration in each specimen. Furthermore, if both the ranges of increase and decrease were large, we considered that both the moisture concentration and transfer to have occurred in the specimen.

$$(Increase\ range) = (Maximum\ value) - (Initial\ value) \quad (1)$$

$$(Decrease\ range) = (Initial\ value) - (Minimum\ value) \quad (2)$$

In AR-1, the moisture content increased or decreased at MC-20-a, b and slowly increased at MC-30-a, b. Some types of moisture content variations were measured at six points of MC-20 in three specimens. In two specimens (AR-1, 3), the moisture content of MC-20-a increased up to 18.4 and 22.3 %, which then decreased. The moisture content of MC-20-b kept decreasing. When the moisture content decreased, the average temperature was 71.5 ℃. In one specimen (AR-2), both of MC-20-a, b kept increasing until 60 min up to 27.8 and 28.2%. Additionally, the rise in the moisture content at MC-30 in AR-2 was significant. The moisture content increased continuously till it reached 39.9 and 87.0% over the valid range (10–30%) of moisture sensor. The moisture content at the other MC-30 measuring points kept increasing slowly for 60 min. The increase in temperature was similar in six measuring points. The average temperatures and coefficient of variation at 60 min were 85.6 ℃, 3.0% at T-20, and 73.5 ℃, 1.9% at T-30.

In AT-1, the moisture content kept decreasing until the heating stopped at almost all the measuring points. As shown in Figure 7, the mean value of the increase range of AT was 0.4% at MC-30, 0.6% at MC-20, and these were smallest in three conditions. Similar to AR, the increase in temperature was similar in six measuring points. The average temperatures and coefficient of variation at 60 min were 91.0 ℃, 3.0% at T-20, 75.7 ℃, 3.5% at T-30.

In AL-1, the moisture content first increased up to 15.7 to 19.4%, and then decreased. Although, MC-20-b in AL-1, MC-20-a, and MC-30-b in AL-2 showed little increase,

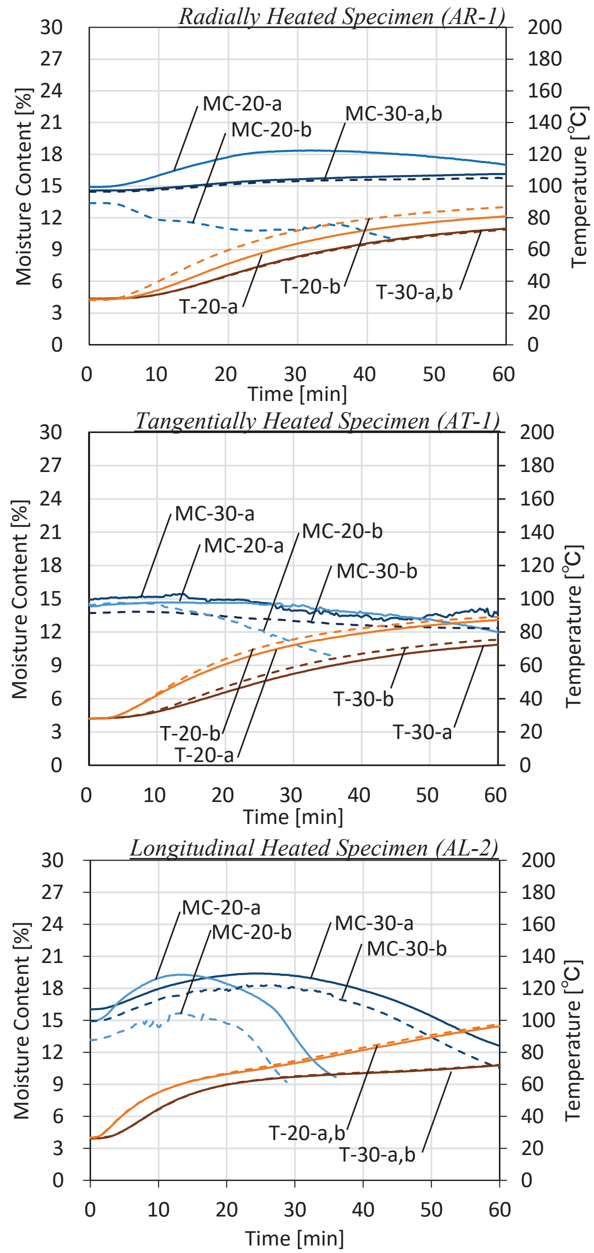
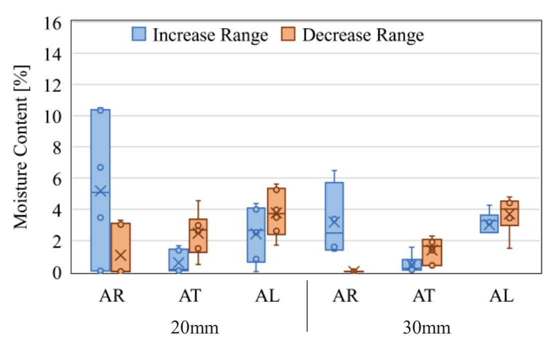


***Figure 6**: Time Histories of Temperature and Moisture Content*



R: Radial heating, T: Tangential heating, L: Longitudinal Heating
20 mm, 30 mm: depth from heating surface
*Values of MC-30-a, b in AR-2 were excepted because maximum value exceeded range of moisture sensor.

***Figure 7**: Increase and Decrease Range of Moisture Content*

https://doi.org/10.52202/069179-0222

other nine measuring points showed the increase and decrease in the moisture content. When the moisture content decreased, the average temperatures of the measuring points were 67.7 ℃ and 65.0 ℃ at T-20 and T-30, respectively. Additionally, the temperature variation was similar in all the specimens. The average temperatures and coefficient of variation at 60 min were 97.6 ℃, 4.3% at T-20, 75.5 ℃, 5.5% at T-30. However, in AL, the increase in temperature was faster than that in the AR or AT for 20 min; furthermore, the increase in the temperature was almost linear until the end of experiment.
As shown in Figure 7, according to the result of each condition, moisture increase range of the longitudinally heated specimens were as large as the radially heated specimens and 4.2–6.8 times larger than that of the tangential heated specimens and decrease range of longitudinal direction was 1.4–3.6 times larger than that of other direction; however, the result of MC-30 in AR was excepted, as moisture content of the condition kept increasing for 60 min and the decrease range of MC-30 in AR was 0.0%.
Increase of moisture content in radial heated specimens indicated that less diffusion or desorption from measuring points occur in radial direction and possibility of significant moisture concentration. As mentioned above, variation of moisture content in AR specimens was apparently different in each specimen. The water concentration in radial direction can be significantly affected by individual difference of each specimen.
Water transfer, especially the decrease in moisture content was fastest in longitudinal direction. Figure 6 showed large variation of moisture content in longitudinal heated specimens. Furthermore, as shown in Figure 7, both the increase and decrease of moisture content were largest in the three conditions. Moreover, Figure 8 showed that the rate of moisture content range was largest in the three conditions.
Considering that the increase of moisture content indicates concentration of water at measuring points and decrease of moisture content indicates vaporing or diffusion or desorption at measuring points, significant increases and decreases of moisture content indicate the occurrences of both water concentration and diffusion or desorption in the longitudinal heated specimens.

3.2.3 CORRELATION BETWEEN MOISTURE CONTENT VARIATION AND TEMPERATURE

Figure 8 shows the relationship between the changing rates of temperature and moisture content. We obtained the ongoing change in the rate of change in moisture content by calculating moving average of the two minutes moisture content change for each specimen and averaging those changes of three specimens. In all the conditions, the rate of change of moisture content generally remained in the range of -0.20–0.20 [%/min] and there was small difference between values of 20 mm depth to 30 mm depth. The rate of change of moisture content in AT generally took negative values; whereas for AL and AR, the rate increased from room temperature to 49.1–53.3 ℃ and then decreased, with negative rates at approximately 65 °C in AL and 76 °C in AR. AL exhibited a significant decrease in the negative range and took a minimum rate of moisture content change of -0.49 [%/min] in the high temperature range above 70 °C. The minimum rate of change of moisture content in AL was 2.6 times larger in absolute value.
Figure 8 showed that the rate of moisture content range of longitudinally heated specimens was largest in three conditions and the increase and decrease of moisture content was largest in longitudinally heated specimens as mentioned above. These results clarify higher mobility of water in longitudinally direction.
For several wooden properties, such as permeability, diffusivity of water and diffusivity of vapor higher water mobility in the longitudinal direction (along the grain) was reported compared to that of radial or tangential direction (across the grain). Kawabe [5] reported that the permeability along the grain was 5.6–9.3×10^3 times larger than that across the grain. Yokota [7] reported that diffusivity of water and vapor along the grain were 5–20 and approximately one hundred times larger than those across the grain respectably. According to these reports, the anisotropy on diffusivity of water was near to the anisotropy of increase or decrease of moisture content and

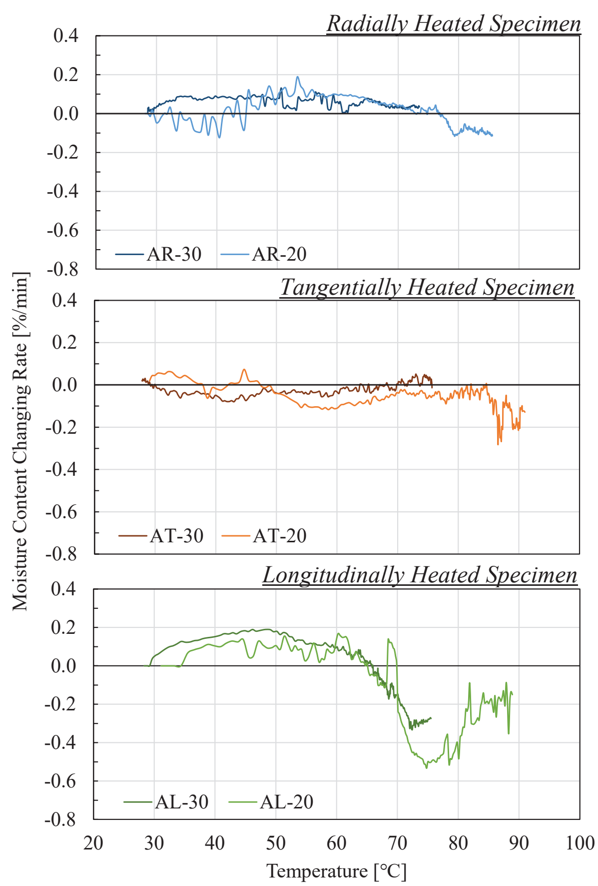


Figure 8*: Relationship of Temperature and the Rate of Change in Moisture Content*

https://doi.org/10.52202/069179-0222

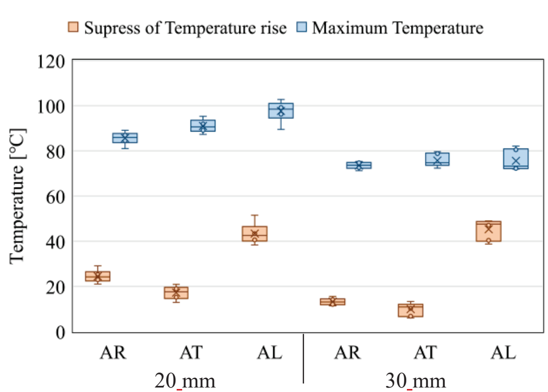
the rate of change in the moisture content, whereas the anisotropy of the permeability and diffusivity of vapor were ten to hundred times larger than that of the isotropy we measured in this experiment. Considering that the rate of change in the moisture content decreased in the range of 20–30 °C, which is lower than the vaporing temperature, vaporing was considered to be occurring inactively when the rate decrease.

Therefore, we consider that properties affect transfer of vapor do not significantly affect the water transfer and mobility of bound water is dominant or other properties such as desorption rate of water on wood tissues limited the water transfer in wood under fire heating.

3.3 COMPARISON OF AIR-DRY AND BONE-DRY CONDITIONS

Figure 9 shows the maximum temperature of Air-Dry condition and suppression of the rise in temperature between the bone-dry to air-dry conditions. Maximum temperature of each condition was AL>AT>AR at both of 20 mm and 30 mm depths; however, the difference was larger at 30 mm depth. The average maximum temperatures were 82.1 °C in AL, 79.6 °C in AT, 74.0 in AR at 30 mm depth, and 102.7 °C in AL, 95.3 °C in AT, 86.1 °C in AR at 20 mm depth. The rise in the temperature of air-dry specimens were reduced to be lower than that of bone-dry specimens in all the heating directions. The temperature differences between the air-dry specimens to bone-dry ones on 60 min at 20 mm and 30 mm depth were 9.9, 17.2 °C in AR, 12.8, 24.1 °C in AT, 45.3, 43.4 °C in AL on average, respectively.

The difference at 30 mm depth from the heating surface in AL was 1.8–2.5 times at 20 mm depth and 3.6–4.6 times larger than for the other conditions; suppression of the rise in temperature was the largest in longitudinal direction. Furthermore, the suppression of the rise in temperature in AL at 20 mm depth was as same that of the suppression of 30 mm depth; however, that in AR or AT at 20 mm depth was twice larger than that of the suppression at 30 mm depth.



R: Radial heating, T: Tangential heating,
L: Longitudinal Heating
20 mm, 30 mm: depth from heating surface

Figure 9*: Suppression of Temperature rise and Maximum Temperature at 60 min*

From the result, it is evident that the moisture content can suppress the temperature rise, and the effect is apparently largest in longitudinally heating.

We considered that the suppression of temperature rise was caused by large heat capacity of water. The heat capacity of water is approximately 4.18 [kJ/(kgK)], which is approximately 3.5 times larger than that of heating capacity of Bone-Dry woods [6]. This is the reason for Air-Dry specimens having 1.3 times larger heat capacity that that of Bone-Dry specimens and the difference caused the difference of temperature rise.

Furthermore, anisotropy of suppression of temperature rise is caused by anisotropy of transfer of water. At first, temperature suppression in wood under fire heating was caused by difference of heat capacity as mentioned above, indicating that the moisture is heated instead of wood. Then, the heated moisture is thought to transfer along heating direction as vapor or bound water because of the gradient of vapor pressure or moisture content in wood tissue; furthermore, water can heat wood tissues away from heating surface with lower temperature after the transfer. In this scenario, if moisture transfers quickly and it is released out of wood, temperature rise is further suppressed as moisture does not heat wood tissues. Therefore, the rise in temperature was largely suppressed in the longitudinally heated specimens of which moisture transfer is fastest in three directions.

4 CONCLUSIONS

Following information was obtained measuring time variations of temperature and moisture content in air-dry and Bone-Dry Japanese Cedar specimens under 4.5 [kW/m^2] steady heating for 60 min with Cone Calorie Meter.

(1) Temperature rise of Bone-Dry specimens was larger in longitudinally heated specimens compared to that of the other conditions, and that of the other two conditions were similar. The difference between longitudinally to radially or tangentially heated specimens increased up to 34.7 °C at 30 mm depth from heating surface. The difference between longitudinally heated specimens to radially or tangentially heated specimens at 20 mm depth was as same as that of the 30 mm depth.

(2) Increase in the moisture content was 4.2–6.8 times larger in the longitudinally and radially heated specimens compared to that in the tangentially heated specimens and decrease of moisture content in longitudinally heated specimens was 1.4–3.6 times larger than the other two conditions.

(3) The rate of moisture content changing rate of the longitudinally and radially heated specimens increased up to 49.1–53.3 °C and then decreased. These rates took zero around 65–76 °C. Moreover, the minimum of the rate of moisture content changing of longitudinally heated specimens was 2.6 times larger in absolute value compared to the other conditions.

(4) In all the conditions, the rise in temperature in air-dry specimens was lower than that of bone-dry specimens. In the longitudinally heated specimens, the temperature rise was 1.8–4.6 times largely reduced compared to radially or tangentially heated specimens, and difference of the suppression between 20 mm depth to 30 mm depth was little in longitudinally heated specimens but twice in the radially or tangentially heated specimens.

In this experiment, we noted some future issues. One is discrepancies of the moisture content between the values obtained by sample drying and by moisture sensor, another is the difference of moisture content variation between each specimen in radially heated specimens. Moreover, experiment under conditions of higher heating intensity is required, which can clarify water transfer around heating surface in wooden structural members.

ACKNOWLEDGEMENT

This study was funded by the JSPS program on “Empirical study on heat and moisture transfer in wooden members under fire heating and its mechanical effects”（The Research Leader was Yuji HASEMI）and Waseda University Grants for Special Research Projects (Tokutei Kadai) No.2021C-535, (The Research Leader was Tomoyo HOKIBARA.)

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